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Quality Control of Extrusion Strength for the Petronas KLCC Twin Towers Curtainwall

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Abstract

During the proof loading of the first curtainwall prototype performance test, KLCC Petronas Twin Towers, 4 panels were blown out when bracket components failed. Aluminium alloys 6061-T6 & 6063-T594; tested components showed lower hardness than expected; this was a non-conformance. Extrusion tempering procedures were reviewed and improved; tensile tests were carried out; Student's T small sample analysis, a 99% confidence factor and 1.25 design factor were adopted to determine the minimum tensile yield for each alloy. The non-conformance was deleted. Webster testing was used through production to Quality Control adequate hardness as a pointer to the strength of the alloys.

1. Introduction

Arup Facade Engineering (AFE) was appointed curtainwall Consultant to KLCC for the two towers of the Petronas Twin Towers project in mid 1994. As Principal Engineer, Façade Systems, this paper's author was the leader of AFE's project team. AFE's brief started with the first prototype performance test and included the manufacture, assembly and installation phases of the curtainwall. During the first phase of AFE's involvement, a failure occurred at the curtainwall performance prototype test. Four panels were blown out of the prototype during proof loading. Subsequent Rockwell F tests on aluminium alloy samples indicated a deficiency in their structural properties. This was a quality non-conformance, which had to be investigated and rectified. This paper describes the use of aluminium in the curtainwall industry and for the KLCC curtainwall, the programme of testing to determine structural properties of the aluminium alloys and the QC checks carried through the production run of aluminium extrusions.

2. The KLCC Petronas Twin Towers Development

The KLCC Petronas Twin Towers are the nitized li of the Kuala Lumpur City Centre (KLCC) development in the heart of Malaysia's capital city. The KLCC project comprises more than 17 separate developments, including office towers, hotels, a mosque, a major shopping centre and residential blocks surrounding an inner-city park and recreation land. The Twin Towers are a landmark development in Malaysia's Vision 2020. They represent a feat of engineering unparalleled in Malaysia, moving the country ever closer to its goal of becoming a fully developed nitized lized nation [1]. The towers' structures were made with a central concrete core, 16 concrete columns of 80Mpa concrete and concrete floors poured over steel deck formwork. A bridge links the 2 towers at the Skylobby levels, 41 and 42. The Twin Towers were officially the tallest buildings in the world when they were built, being 446m from street level to the top of the 60 metre spires. They will remain the tallest twin towers for many years to come.

Table 1: Parties Involved in the Twin Towers.

Function		**Tower 1**	**Tower 2**
Concept Architect		Cesar Pelli & Associates Ins of New York	
Detail Architect		Adamson & Assoc. (Can)	KLCCBhd Architects
Project Manager		Lehrer McGovern (M) Sdn Bhd	
Main Contractors		"Mayjaus" JV between MMCE, Ho Hup, Hazama. J.A.Jones & Mitsubishi	JV was between Samsung Engineering & Construction Co, Kukdong & Jasetera
Curtainwall Consultants	Design Phase	Israel Berger (New York)	
	Testing, Manufacture & Installation Phases	Arup Façade Engineering (Australia)	
Structural Engineers		Thornton Tomasetti Engineers (USA) Ranhill Bersekutu Sdn. Bhd.	
Curtainwall design, industrial engineering and overall supervision of manufacture and installation		Harmon Contractors (Minneapolis, USA)	
Curtainwall manufacture and installation		Lucksoon (Malaysia)Sdn. Bhd. Local JV partners with Harmon	

3. The KLCC Petronas Twin Towers Curtainwall

The curtainwall is a nitized (panel) system, fully drained and pressure-equalised. The curtainwall unit frames were assembled from machined aluminium alloy extrusions. They were assembled in Lucksoon's factory about 20km south east of KLCC. The frames had their insulation installed and were fully glazed before trucking to site. At site, the bullnose and teardrop features were added before each panel was installed. Each unit (or panel) is typically 4m tall with a width of 1.3metres. Units typically span from sill to sill, with the mullions fixed with aluminium brackets to channel inserts cast into the concrete at each floor. At installation, each panel interlocks with those around it. Male/female mullions interlock vertically and male/female transoms interlock horizontally at the sill. The whole of the towers' curtainwall comprises some 33,000 units, and façade area of 85,000 square metres. The units were fabricated, assembled and installed on site over a 2-year period, from late 1994 to late 1996.

Table 2: The Main Materials used in the KLCC Curtainwall.

Material		**Supplier**
Aluminium Extrusions	6063 T594 for mullions 6063-T5 for transoms and beads 6061-T5 for brackets	Aluminium Company of Malaysia Sdn. Bhd. 'Alcom'
Glazing	Vision Glass; 14.38 laminated with green tint	Malaysia Sheet Glass Sdn Bhd
	Spandrel glass; grey colourback (fired-on ceramic)	Viracon Glass (USA)
Stainless Steel Grade 316	Sheet, including Cambric embossed spandrel panels, 2.5mm	Avesta Sheffield (Sweden & UK)
	Bullnoses	Matsui (Japan)

4. Aluminium Use in the Curtainwall Industry

From the late 1960s when curtainwalls started becoming popular, the curtainwall industry adopted the use of aluminium alloy extrusions for its components, i.e. mullions and transoms. Only aluminium alloy was capable of being formed (extruded) into the complicated shapes required at an affordable price. A curtainwall forms the continuous façade (cladding and windows) on a building. Extrusion volume is achieved from the area required to cover a large building; major projects have purpose-designed extrusions which may be unique to that project.

The curtainwall industry has always been a cutthroat one and the choice of aluminium alloy has always been driven by cost towards the lowest cost alloy available on the market. The most commonly used alloy worldwide is 6063-T5, as this was the least expensive extrusion material. It is the lowest price because it is the easiest to extrude, has low alloy content with no extra temper process, but it also has the lowest structural strength. The curtainwall industry has never dictated to the aluminium industry what should be supplied, but has always accepted the alloys available. For the extra strength sometimes required by mullions, 6063-T6 has been used and 6061-T6 high strength alloy has been used since the early 1980's for brackets. The T6 temper is an accelerated ageing oven batch process.

Since the early 1990's 6063 alloy has been replaced in Australia by 6060. Although a complete set of structural properties are not available, the suppliers advise that the properties are identical to 6063. The suppliers also advise that 6060 is slightly more ductile and easier to extrude. In Australia, the Aluminium Structures Code [3], AS1664 had a major re-write in 1979 and again in 1997. Minimum property values in the Code remain the same as they were in the 1960s, despite the fact that quality control has vastly improved. As properties can now be guaranteed much more precisely, the actual minimum properties are higher.

Alloy 6063-T5 has a typical yield of 145MPa in tension, but the minimum yield in the Code is still 110MPa. This minimum value could be increased in line with the higher quality of production technology now available, making the alloy effectively stronger and less expensive, as less material would be required to achieve required strength in a member.

The Code has also not been updated in line with the use of new alloys. Alloy 6060 is almost universally now used in Australia, but is not listed in [3] AS1664. So far the compressive strength in yield is not available from any of the suppliers; the advice is that all 6000 series alloys have the same yield value in both tension and yield. The compressive yield value is required to determine instability in beams and struts. Alloy 6060 is being used unsanctioned by the Code [3].

5. KLCC Curtainwall Prototype Performance Test

The first prototype of the KLCC curtainwall was tested at the Construction Research Laboratory (CRL) in Miami in June 1994. The prototype was built as the external wall of an air pressure/suction box. It was made of 57 units, 3 storeys high. The specified tests included:

- structural test (measurements of mullion deflection under static air pressure),
- air infiltration (air leakage through the curtainwall),

- water penetration (under static air pressure and dynamic pressure from an aircraft engine),
- seismic racking (the middle floor beam of the prototype was racked ± 20mm),
- building maintenance unit (gondola) loading, and
- proof test (static air pressure loading to 1.5 times the design load).

The testing went well until the proof test, when 4 panels were blown out of the test rig. The hooks, which attach the mullions to the floor bracket, were critically distorted under load and released the panels.

6. Investigation into the KLCC Curtainwall Prototype Failure at Proof Load

The investigation to determine the cause of the collapse considered 3 possibilities:

a. Design: A quick check of the calculations indicated that the components were adequately designed.
b. Material: The aluminium alloy was checked for strength in accordance with published [2 & 3] data. Samples of the broken hooks and other components were tested at a local engineering laboratory in Miami. Rockwell F hardness test results, compared with Alcan's (US) graph "Hardness vs Mechanical Properties" gave the indicated yield and tensile strength. The alloys were found to be under strength
c. The Test Rig: All details were closely inspected. It was found that the central beam of the test rig structure had not been properly secured after the seismic test and had moved sideways under the proof load. One hook on each bracket plate had jumped off its retainer thus overloading the next hook, which failed. The collapse stopped at the corner panel, which was double-fixed.

The prototype subsequently passed the proof test with four replacement panels and without modification to the design and with bracket components identical to those that had failed in the proof test. It was therefore evident that the test rig was the one cause of the collapse and that the prototype-tested material was adequate, despite not meeting the published structural data values in the hardness tests. The proof loading probably did not exceed the material yield, because of the difference between actual yield and the design values; ie, the minimum yield values listed in the Codes [2, 3].

The Alcan graph indicated a minimum expected result of Rockwell F hardness of 85, for 6061-T6. Rockwell F test results averaged approximately 70. Alcom data indicated that the T594 temper gave a 14% better strength than 6063-T6; the Alcan graph indicated a Rockwell F hardness of 70 to 80. Typical yield of 6063-T6 is 205MPa and for 6063-T594 is 235 MPa. The test result was also only 85% of the expected result. The results were less than satisfactory. The Rockwell F tests were performed in Miami, because this test was quick, easy and available. The tests were carried out on extrusion surfaces. The material on the outside of the extrusion (the skin) may have different properties from the body of the extrusion within. The Rockwell tests were therefore considered indicators only.

The fact that the published data values for the alloys were not met by the Rockwell F tests was of great concern. This was because it was industry practice to accept the alloys used for curtainwalls, accepting entirely the advice of their structural properties from the manufacturer. Here was a case where the material supplied did not appear to meet the claims of the supplier. In terms of Quality Assurance, a non-conformance had been found and a full investigation of all alloys was required.

7. Determination of Typical Yield Stress

Both the Australian [3] and British [4] Aluminium Structures Codes allow testing to confirm structural properties. AFE designed a testing and analysis programme to determine design values for the production alloys already used in design and performance testing of the curtainwall. This was based on tensile test specimens of production extrusions.

Alcom provided billet certificates. These were compared favourably with compositions listed in "Aluminium Standards" [2] from the Aluminium Association, Inc. This indicated that the problem was the tempering process. Alcom reviewed their tempering process and produced 4 batches of 6063-T594 & 6061-T6. From the extrusion material Alcom machined tensile test samples in a conventional dumbbell-shape. Tests were tested on Alcom's universal testing machine, at their extrusion plant in Subang Jaya, near Kuala Lumpur. A small sample statistical analysis using "Student's T" formulas were used to determine the mean, standard deviation and the 99% (1% fractile) values for the population assuming a normal distribution. The 99% confidence level or chosen characteristic value is the value above which 99% of the population is contained under the normal distribution curve. Alternatively, if all extrusions were tested, 99% would give a yield value above the 99% confidence level. This gives:

the characteristic value $f_c = f - s \cdot t$, (1)

where f = the average of the test specimens,
s = the standard deviation, and
t = the Student's T value for a 1% fractile and 'n' samples.

8. Determination of Minimum Design Stress

From published data typical and minimum yield strengths for 6061-T6 are 255 [2] and 220MPa [3] and for 6063-T5 are 145 [2] and 116 [3], respectively. The factor of 255/220 is 1.16 and 145/116 is 1.25. The more conservative factor of 1.25 was adopted for all alloys. This gave:

minimum yield stress $F_{ty} = f_c/1.25$. (2)

Following the requirements of AS1664 Table 7 [3], the maximum permissible tensile stress was obtained by dividing F_{ty} by the factor n_y of 1.65. The determined values were only a few percent below the minimum values used by Harmon for the design, ie published by Alcom. The calculations for the curtainwall were adjusted accordingly and found to be satisfactory with the marginally lower permissible stress values. AFE were satisfied that the non-conformance had been rectified. Firstly, the proof test of the performance prototype passed without permanent set of any members and secondly, the structural qualities of the aluminium were now adequately understood.

9. Quality Control Checks for the Production Run

The final concern was to ensure that the correct strength of all alloys was maintained through the full production run. The test had to be quick, simple and reliable. For this Webster testing was adopted. The Webster tester is a hand-held hardness tester, which works like a pair of pliers to push a small ball into the metal surface. The Webster test is not nearly as accurate as the Rockwell test, if the test results are used to determine the hardness. However, the Webster gives repeatable results if there is a “control” sample for comparison. Both Harmon and Alcom had their own Webster testers and acceptable values were determined for each machine, using the already tested tensile test samples as the control. Harmon carried out 5 Webster tests on each crate of extrusions that arrived at the Lucksoon factory. The test results were recorded as part of Lucksoon’s factory QC procedures and were carried out for the full production run of extrusions.

10. Summary and Conclusions

Contrary to industry practice, a curtainwall designer should not blindly assume that aluminium alloys always have the properties claimed by the manufacturer. If there is any doubt, the manufacturer should be asked to provide test data on actual project extrusion material to prove the alloy properties. The Australian and British Aluminium Structures Codes allow proving of structural adequacy by testing and this can be applied to aluminium alloys which are not specifically listed in the Codes.

This paper has described a programme to determine alloy properties, based on tensile test samples. Twelve samples were tested from different four different extrusion batches. A small sample statistical analysis was carried out on the results and the minimum properties were determined as 1/1.25 times the 1% fractile value. Quality of the product through the production run was QC checked by Webster Testing.

To date, the KLCC Petronas Twin Towers project has stood up to the elements and remains a landmark building.

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